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A VALIDATION OF FIRST-ORDER DETONATION SHOCK DYNAMICS THEORY

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14. ABSTRACT

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High energy explosives are used in a variety of applications, from military to industrial processes. The use of embedded, inert material “wave shapers” is a primary method to customize the detonation front for desired ex-plosive applications. These systems create detonation states that do not follow the simple line of sight, or Huy-gens model and, hence, advanced detonation physics with associated theory are required. The theory of detonation shock dynamics (DSD) is one such description used to pro-vide high fidelity modeling of complex wave structures. A collection of experiments using ultra-high speed cameras is presented as a means of obtaining spatial and temporal characteristics of complex detonation fronts that validate the DSD descriptions. The method of test, operational conditions and results are given to demonstrate the use of high-rate imaging of detonation events and how this vali-dates our understanding of the physics and the capability of advanced detonation wave tracking models.

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ABSTRACT

High energy explosives are used in a variety of applications, from military to industrial processes. The use of embedded, inert material "wave shapers" is a primary method to customize the detonation front for desired explosive applications. These systems create detonation states that do not follow the simple line of sight, or Huygens model and, hence, advanced detonation physics with associated theory are required. The theory of detonation shock dynamics (DSD) is one such description used to provide high fidelity modeling of complex wave structures. A collection of experiments using ultra-high speed cameras is presented as a means of obtaining spatial and temporal characteristics of complex detonation fronts that validate the DSD descriptions. The method of test, operational conditions and results are given to demonstrate the use of high-rate imaging of detonation events and how this validates our understanding of the physics and the capability of advanced detonation wave tracking models.

1 BACKGROUND

1.1 The Need for Advanced Modeling

A primary driver for the need to develop more efficient models of explosive events is brought about by the issue of length scale. Reaction zones of detonation fronts are only fractions of a millimeter and using direct numerical simulation methods forces one to resolve or discretize that zone with 50 to 100 computational "elements" or "cells". The shock front is where pressures near instantaneously change from ambient (1-atm) of the solid phase explosive to hundreds of thousands of atmospheres within the chemical decomposition regime of the "reaction zone" and then decay back to hundreds of atmospheres of pressure in the expanding gas products field. State variables of specific volume and temperature also change rapidly over the extremely small reaction zone. The numerical stability condition, or Courant-Friedrich-Levy condition, limits the computational time step based on the smallest spatial cell or element that information can be calculated across. Since most munitions are on the order of meters, then these calculations quickly become time intensive with some taking weeks to complete. The detonation propagation algorithms must accurately capture the proper state variables in order to advance the front and give accurate time-of-arrival and loading conditions to the inert material being acted upon. Therefore, more efficient methods are required to provide high fidelity representation of the physics driven by small-scale phenomenon for the global, larger scale event. Detonation Shock Dynamics (DSD) is one such solution (Stewart and Bdzil 1998).

A conventional detonation propagation model assumes that the detonation shock propagates normal to itself at the Chapman-Jouguet (CJ) velocity. This motion rule is called the Huygens construction, or line of sight. One can use this propagation rule to propagate a front through the explosive geometry and calculate the time of arrival (TOA) at the surfaces of the inert materials. Knowing the arrival time of the fronts from this simple engineering rule had been almost enough to work out basic designs. But, given the demands of more complex systems with multiple ignition points, smaller charges, complex geometries for the explosive charge, and the desire to engineer complex sequences of synchronous actions, this simple model and motion rule does not provide enough accuracy.

1.2 Review of Detonation Shock Dynamics

The asymptotic theory of detonation shock dynamics refers to hydrodynamic flow theory that corrects a near planar detonation flow normal to the shock to account for changes due to the shock curvature and a higher order theory that includes unsteady effects. The theory assumes that the radius of curvature of the shock is large compared to the length of the reaction zone that supports the detonation. The term "Detonation Shock Dynamics" (DSD) describes both the asymptotic theory and its engineering application (Bdzil and Stewart 1988). The simplest theory of DSD approximates the local detonation velocity normal to the

shock, D_n,as being the Chapman-Jouget velocity, D_{CJ}, adjusted by the local total curvature, κ, relation,

$$D_n = D_{CJ}(1 - \nu\kappa) \tag{1}$$

where ν is an empirical constant. This curvature relation is used in conjunction with an equation of state and reaction rate law to provide a new motion rule that can be used to make refined engineering prediction of the detonation process in desired applications. The DSD motion rules are intended to replace the traditional Huygen's construct that simply transmits the information at a constant D_{CJ}. Optical high-speed smear camera techniques can be used to obtain the D_n-κ relationship (Hull 1993 and Lambert 2005).

An equation of state (EOS) is a description of the energy, pressure, specific volume and burn fraction relationship $e(p,v,\lambda)$ for the reacting explosives. The rate law governs the rate at which the reaction progresses from the solid phase to complete gas products $r(p,v,\lambda)$. The specific forms of the EOS and rate laws are not given or required here, but are mentioned for completeness. There are standard experiments, some using optical methods (Lambert, 2005) for calibrating the EOS and rate law models.

2 VALIDATION EXPERIMENTS

A series of validation experiments are typically required to confirm these models can provide the accuracy and fidelity of computing the response in real explosive applications. The ability to accurately track the wave front in complex detonation scenarios is of high interest and is the primary topic of interest for this section. The Munitions Directorate has two-dimensional (2-D) and three-dimensional (3-D) research codes that were developed by the University of Illinois specifically for addressing problems of interest (Yoo 2003). These experiments and their hardware were configured to capture the physics of interest within actual explosive applications but with as simplified geometries as possible and with well-characterized materials. They provide a means to validate the ensemble of physics models including the equation of state and rate laws.

2.1 2-D Axisymmetric "Passover" Experiment

One method of "wave shaping" is to insert an inert object within the reactive flow field. This common method of wave shaping causes the oncoming detonation to track around the object and, hence, allows a tailoring of its shape. The "Passover" Experiment, shown in Figure 1 was designed to provide validation of a 2-D axisymmetric explosive design. It is a "self-light" method – meaning the photons generated within the detonation reaction zone itself exposes the film. The primary data is the time-of-arrival of the wave exiting the top surface (explosive/water interface) of the assembly. The embedded disk of lead serves as an "obstacle" to transform a simple hemispherical, incoming detonation wave to a reasonably complex flow. It forces the simulation tools to calculate the wave progression across a broad range of curvatures, including the transition from a divergent to convergent regime.

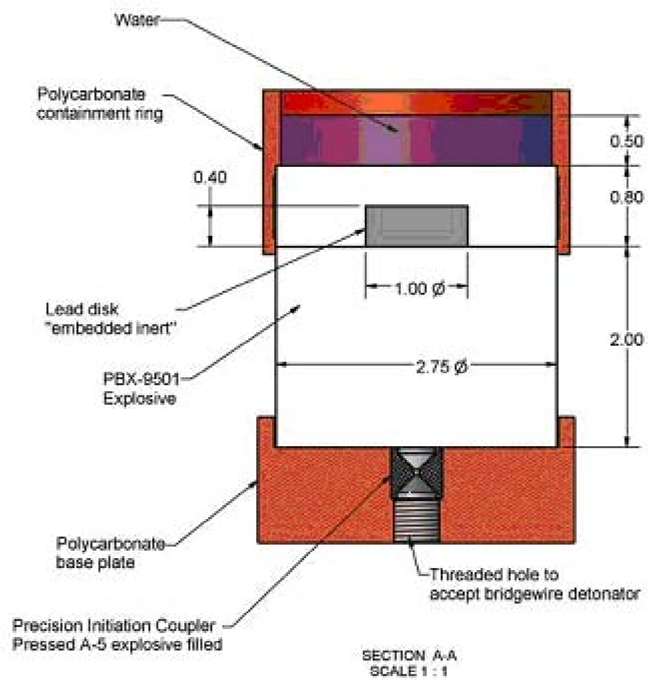

Figure 1: Cross-section View of the 2-D "Passover" Experiment

2.2 Experiment Description

The assembly consists of four significant components. The first is the main explosive charge of PBX-9501. PBX-9501 is one formulation that has its D_n-κ relationship and suitable equation of state/rate law pair characterized. The main charge consists two pieces: a lower solid cylinder of 69.85-mm (2.75-inch) diameter by 50.8-mm (2.00-inch) long and an upper cylinder of same diameter but with length 20.32-mm (0.80-inch) and having a 25.4-mm (1.00-inch) diameter cavity bored to 10.16-mm (0.40-inch) depth in one end. The second component is a disk of pure lead, machined to fit the cavity in the top explosive piece. The third component is the polycarbonate hardware that physically locates the explosive cylinders together and holds the initiation system precisely at the centerline of the base charge. The initiation system is the fourth component of the experiment assembly. A precision initiation coupler (PIC) is located up against the base of the lower charge. It is simply a steel cylinder with an "hour-glass" internal cavity that is filled with Composition A-5 explosive. An ex-

plosive bridge-wire detonator initiates the PIC that, in turn, centers the detonation and outputs a hemispherical wave.

At time zero, a single detonator ignites the bottom surface. A hemispherical (convex with positive curvature) detonation shock front propagates through the explosive until it encounters the embedded, inert disk. The shock speed in the lead in much lower than the detonation velocity and, thus, the wave diffracts around the disk's geometry. The axial symmetry of the disk and the encountering wave transforms the leading shock into a torroidal shape. As the wave continues around the leeward side of the disk the "hole" closes up and interacts in a symmetrical implosion type of event. The wave structure at this point is the shape of an 'm" if viewed as a 2-D slice through the centerline. The outer regions are of unperturbed, convex curvature while the central region is a highly concave domain with high negative curvature. The detonation front then reaches the top surface of the charge and is quenched by the water.

2.3 Diagnostics – The Imacon 468 and Cordin 132A

Time-of-arrival is the primary data of interest. The Cordin 132A smear camera viewed the top surface of the apparatus with a 100u wide slit positioned across the centerline. The images in Figure 2 show the smear camera images from two experiments. The camera used 70-mm format TMAX ISO3200 black and white film, writing at 12mm/us. One is of the exact configuration of Figure 1 while the other is a similar experiment but done without the lead disk and the top piece of explosive (i.e. just the bottom 2-inch length of explosive) to get data of purely a single hemispherical detonation front. The figures show the wave profile as it breaks out on the explosive/water interface and this data is used to obtain time-of-arrival information.

A DRS Technologies Imacon 468 equipped with 8-framing channels was used in parallel to the Cordin 132A camera. The images in Figure 3 show the global view of the event for the charge not having an embedded disk. It is simply a single point initiation of a 2-inch cylinder and the images are of the detonation front traveling from the rear of the charge and, in this vantage point, coming out of the plane of the page. The frames are 70ns in exposure with 150ns interframe time. Frames from 1-3 show the glow of the hemispherical front within the PBXN-9501 charge. The explosive is translucent under this intense light source. Frame 4 is just after the hemispherical shell of a front intersected the plane of the explosive/water interface giving an 'O' shape (think of a slice through a hemispherical shell). Frames 5-8 show the expanding front it's radius grows and the truncated hemisphere analogy gives the appearance of a wave traveling radially outward. The left-most image of Figure 2 is the simultaneous smear record of this event. The interesting physics aspect of this image sequence is that one is now looking at the instantaneous transition of solid phase explosive to its gas phase detonation products. The imaging time is below that at which the product gases have time to move outward and obscure the view. Pressures on the outside radius of the detonation front are at ambient, 1-atm pressures while that just inside the radius of the detonation front are approximately 350,000-atm.

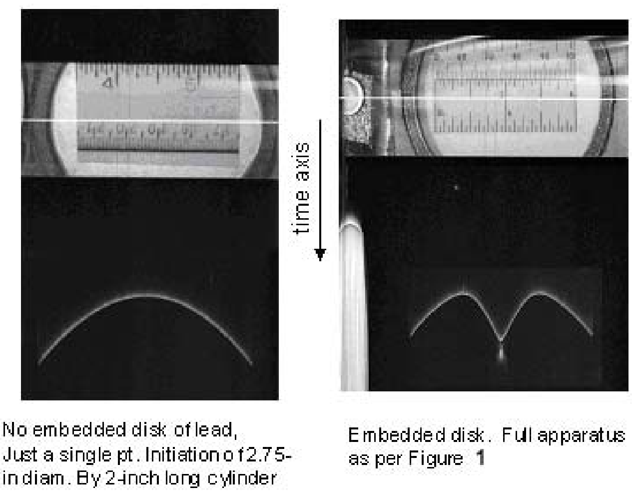

Figure 2: Smear Records of Passover Test with No Embedded Inert (left), with Lead Disk (right)

The image sequence of Figure 4 shows the wave structure for that of the "Passover" assembly in Figure 1. The corresponding smear camera image is that of the right image of Figure 2. Frames 1-5 of Figure 4 show the wave inside the charge as it travels up and around the lead disk. Note the central black region in frames 1-4 are because the disk is obscuring the light at the central region of the hemispherical wave and the time of frame 5 is when the wave is diffracting around the disk. Breakout of the wave on the top explosive/water surface occurs between frames 5 and 6. In frame 6 one can see the torroid shell structure intersecting the plane of the explosive surface and now there is a detonation collapsing radially inward and one moving outward. These opposing detonation fronts continue and frame 8 is opportunistic because it captures the collision of the inward running wave as it is just collapses on centerline. These images were captured using 60ns exposure duration with 150ns constant interframe time.

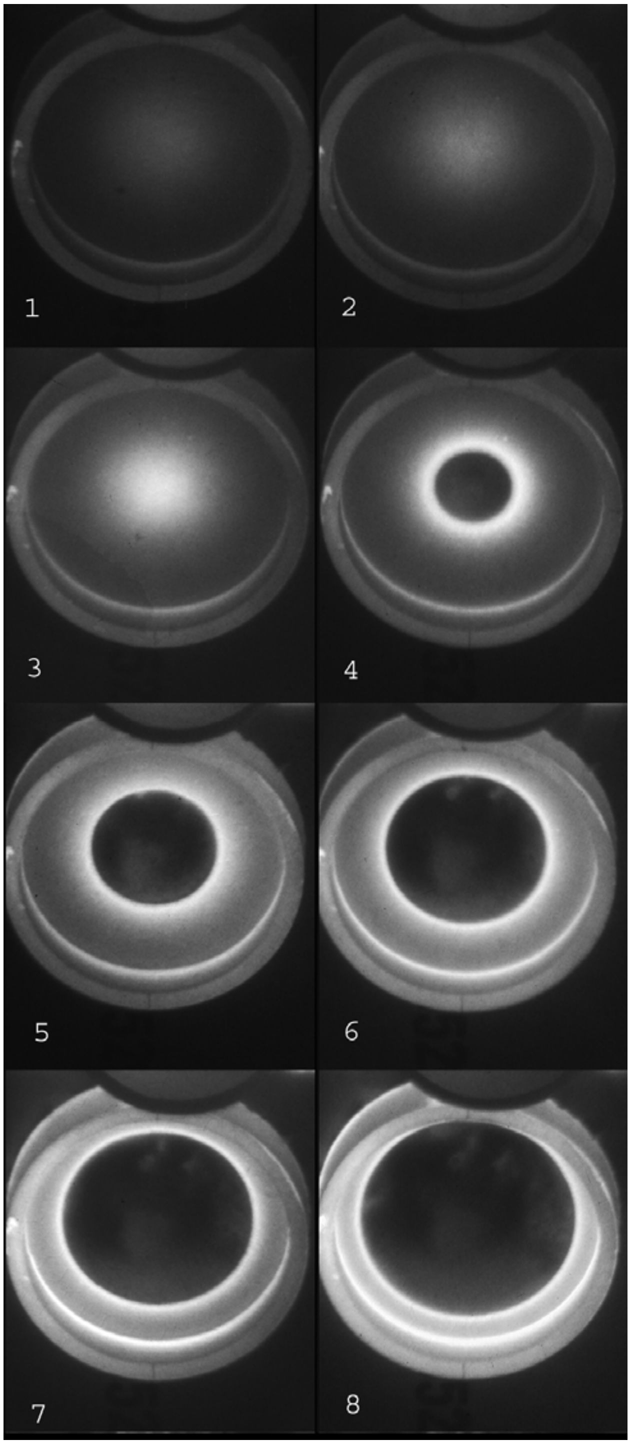

Figure 3: Imacon 468 Image Sequence of Single Point Detonation of a Right Circular Cylinder of PBX-9501 (No Inert Disk)

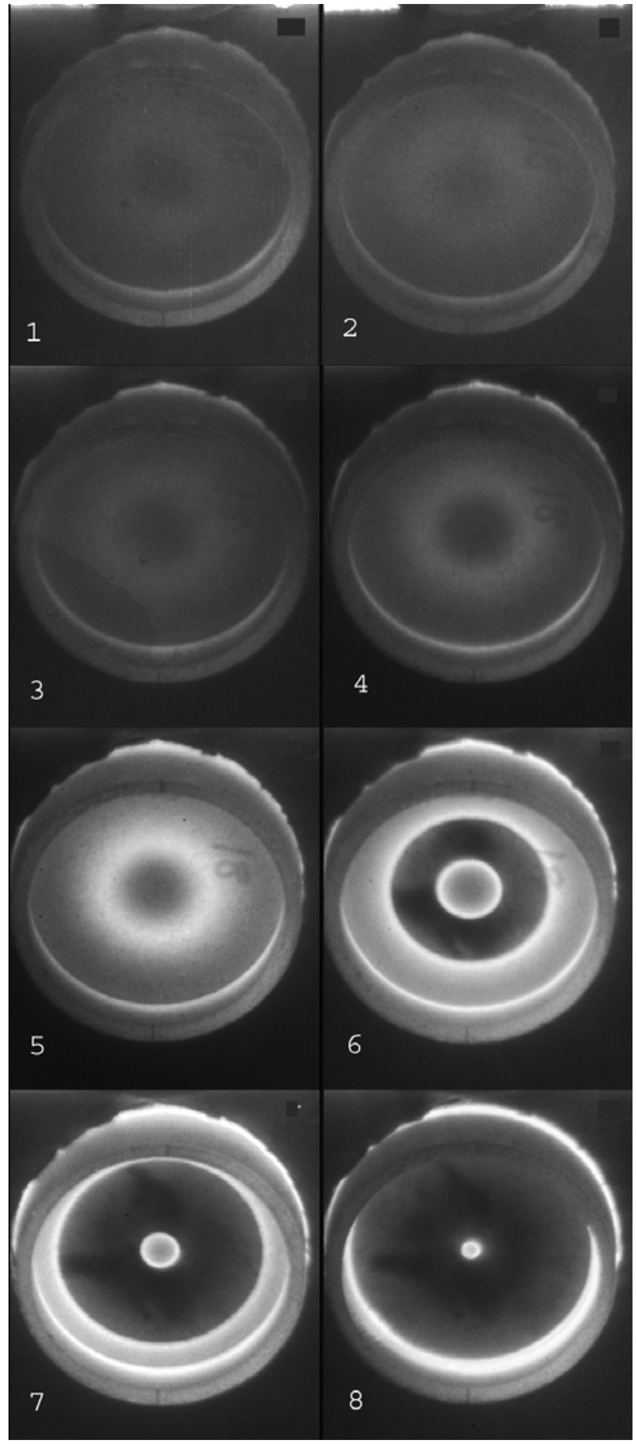

Figure 4: Imacon 468 Sequence of the “Passover” Experiment using Hardware in Figure 1.

2.4 Results and Comparison With DSD Theory

Four experiments of the Passover configuration were conducted. Their smear records (all were similar to that of the right image in Figure 2) were digitized to give time-of-arrival across the diameter of the charge. This data is shown in Figure 5 along with that from a 2-D simulation code, called "2-D Wavetracker", that has the DSD-based motion rule. Also, superposed is the Passover experiment simulated using common Huygen's construct and that of a direct numerical simulation (DNS). The DNS is considered an exact solution by solving the full set of Euler equations with high-order solvers. Recall though, that the DNS represents the computationally intensive method that the DSD-model seeks to relieve. All data is given with the first breakout time adjusted to give the collection the best overall fit.

The DSD and DNS records are nearly the same with an absolute time difference of less than 0.05us, except in the center region.. The Huygen's construction assumed constant normal shock speed of D_{CJ} = 8.86 mm/us. The time-of-arrival at the top surface of the Huygens is about 0.200us shorter (overall) than that of either the DSD or DNS results. The DSD result has greater discrepancy with the DNS in the central, colliding wave region that may indicate inappropriateness of the first order approximation and its assumption of small reaction zone thickness-to-local curvature.

$$\kappa = \frac{l_{rz}}{R} << 1 \quad \text{where } l_{rz}\text{= reaction zone thickness} \qquad (2)$$

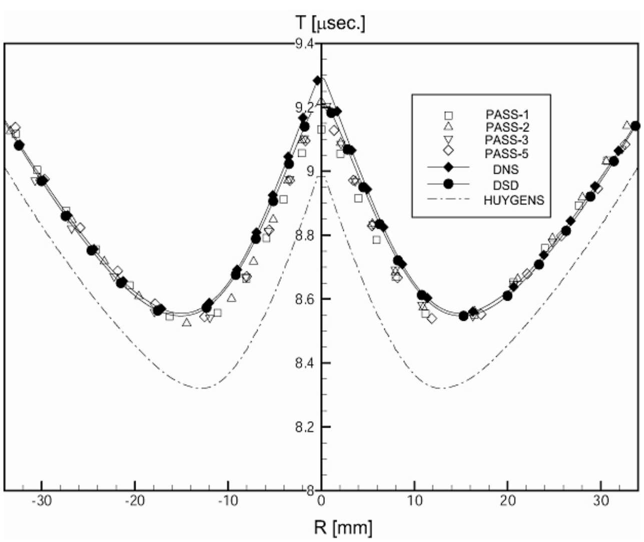

Figure 5: Passover Experiments ("PASS-1", "PASS-2", "PASS-3", and "PASS-5") Compared with DSD-model Motion Rule, Huygens Wave, and Direct Numerical Simulation (DNS).

A 2-D axisymetric view of the isochronal plot for the DSD-model is given in Figure 6. One can see how the wave front is transformed from the hemispherical shell to the torroidal shape as it encounters and sweeps the lead disk to the interacting structure. Note the variation in curvature of the resulting wave structure as it exits the top of the assembly.

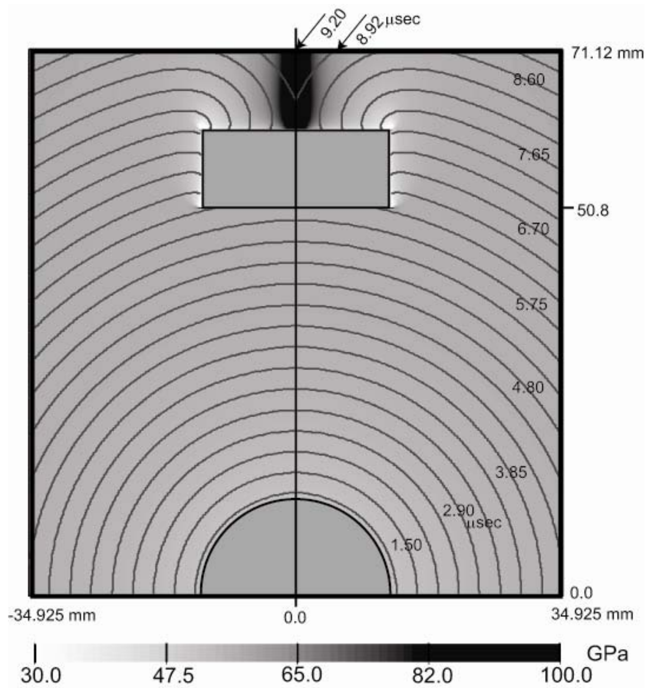

Figure 6: Isochronal Contours for the DSD-based Motion Rule Model of the Passover Experiment.

3 CONCLUSIONS

The Passover experiment generates a large variation in the normal detonation velocity and produces a reproducible and tractable means by which to validate detonation front tracking models. The selection of time-of-arrival of the shock at a known location is but one of many parameters of possible comparison. For many explosive-metal applications, it is a critical parameter and should be considered a fundamental one that simulations should match. The Passover configuration represents such applications but in a well-controlled, well-characterized experimental test bed.

The DSD-WaveTracker tool with its associated equation of state and rate law shows promise as a computationally efficient, but accurate, model to use in further designs and applications. The absolute difference of 0.04us in TOA between the DSD and DNS results is only a 0.4% difference for the total time of wave propagation along the length of the charge. The Huygen's wave construct (recall

that this is the predominately used rule) was shown to be an order of magnitude larger in time discrepancy of the waves arrival.

Excellent agreement between experiment, theory, and direct numerical simulation was achieved. The level of agreement is encouraging because it indicates that one will be able to use these models for real explosives and more accurately predict the response of complex systems.

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